

## Air-Sea and Lateral Exchange Processes in East Indian Coastal Current off Sri Lanka

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Award Number: N00014-13-1-0199

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### LONG TERM GOALS

The long-term goal of our research program is to understand sub-seasonal processes, from small-scale mixing to the reversal of monsoonal currents, in the Bay of Bengal (BoB) and around Sri Lanka and the role of regional air-sea interactions in their dynamics. The research is conducted in the context of the ASIRI-EBOB ONR DRI, and in conjunction with the ongoing ASIRI-RAWI project, which is funded under the Northern Arabian Sea circulation autonomously researched (NAScar) DRI. The PIs seek long term collaboration with Indian Ocean countries (IO), through partnerships and capacity building.

### OBJECTIVES

The objective for FY 2015 was to understand from small to meso-scale processes in the southern BoB during the southwest monsoons, including regional circulation, internal waves and mixing in the upper ocean, all of which have a bearing on local air-sea fluxes. The project seeks to collect hydrographic data sets in the international waters (R/V Roger Revelle) and in Sri Lankan coastal waters (R/V Samuddrika). The measurements include thermohaline stratification, currents and the kinetic energy dissipation rate. The capacity building is directed at Sri Lankan research community through training of graduate students and local scientists, in close collaboration with the Naval Research Laboratory's EBOB Project (PI: Hemantha Wijesekera).

### APPROACH

The University of Notre Dame (UND) group conducted CTD and ADCP measurements in the southern BoB onboard R/V Roger Revelle and in Sri Lanka coastal waters using R/V Samuddrika. The data analysis is centered on internal wave dynamics in the Sri Lankan Dome area and turbulence in Sri Lanka coastal waters. The group deployed a VMP, CTD and ADCPs, as appropriate, from the research vessels.

The capacity building component includes participation of scientists from partnering countries in the US-led field campaigns at BoB as well as training of graduate students at UND in analyzing oceanographic and atmospheric field data. A group of technicians and engineers from the US conducted hands-on training of partner-country technical personnel in setting up and operating state-of-the-art instruments.

## WORK COMPLETED

**A.** The Sri Lankan collaboration led to a number of drifter launchings, deployment of gliders and setting up of a mooring station in the Sri Lanka EEZ during research cruises of R/V Samuddrika (Chief Scientist: Mr. Priyantha Jinadasa), which helped the work of several US ASIRI investigators. The cruises conducted so far by R/V Samuddrika are listed below. The processing of data of these cruises is afoot.

	Date	Location	Work done
1	2014 Feb, 05-07	Beruwala	Instrument calibration and installation around Beruwala area. A test survey on CTD, vertical microstructure profiler (VMP) and acoustic Doppler current profiler (ADCP) was conducted in southern Sri Lanka. Seagliders were deployed during the cruise.
2	2014 Feb, 13-15	Baticaloa	Seaglider deployments in the east coast and south of Yale (Seagilders 169 and 122). Signal from Seaglider 122 was lost on 19 <sup>th</sup> February, but were detected again after six month from Maldives. The glider was recovered. Seaglider 169 gave useful data before her recovery.
3	2014 April 22-25	Beruwala - Weligama	A survey along the southern transect ~ 120 km. Sampling interval was 10 km for the first six locations, and 20km thereafter. CTD, VMP, ADCP and zooplankton data were collected.
4	2014 June 13-15,	Trincomalee/ Baticaloa	The survey was conducted to recover Seaglider 169. This was a joint effort between NARA and University of Washington. GPS transmission was lost and the location of the glider was pinned using acoustic technology.
5	2014 July 13-19	Trincomalee/ Baticaloa	ADCP mooring deployed (acoustic release malfunctioned). Calibration of VEMCO sensors for ADCP mooring at 100m water depth on the eastern transect to sample bottom boundary layer currents
6	2014 July 22-23	Baticaloa	Extricated a lost ADCP mooring
7	2014 Aug 11-14		Seaglider 167 and 3 drifters deployed
8	2014 Sep 09-16	Trincomalee	Eastern transect from nearshore Baticaloa to 125 km offshore. CTD, VMP and ADCP surveys conducted along with zooplankton sampling. First 5 samples with 10km spacing and 20km thereafter.
9	2014 October 1-3	Trincomalee	Drifter deployments using a Sri Lanka Navy boat
10	2014 October 20-30	Trincomalee	Deployment of two Seagliders and PIES (Pressure inverted Echo Sounder) was planned, but delayed pending MOD approval.
11	2014 Nov 14-16	Trincomalee	PIES deployment in the east coast and CTD transect
12	2015 February 12-13	Trincomalee	Deployment of three surface drifters in the east coast, along 8°N. This was done with the help of Sri Lanka Navy.

13	2015 April 06-07	Trincomalee	Deployment of three surface drifters off Trincomalee along 8°N with the help of Sri Lanka Navy.
14	2015 April 28-30	Weligama	ADCP and CTD measurements along a southern transect. Four surface drifters were deployed.
15	2015 August 04 -15	Trincomalee	Two Seagliders were deployed along the 8°N transect from R/V Roger Revelle. Recovery is to be done by R/V Samuddrika. Seven SVP drifters were deployed

\* Starting September 2012, with the help of Sri Lankan Navy vessels, SVP drifters were released periodically. To date, a total of 21 drifters have been released in BoB, some of which have now drifted to the Arabian Sea. Samuddrika work was conducted in close cooperation with NRL.

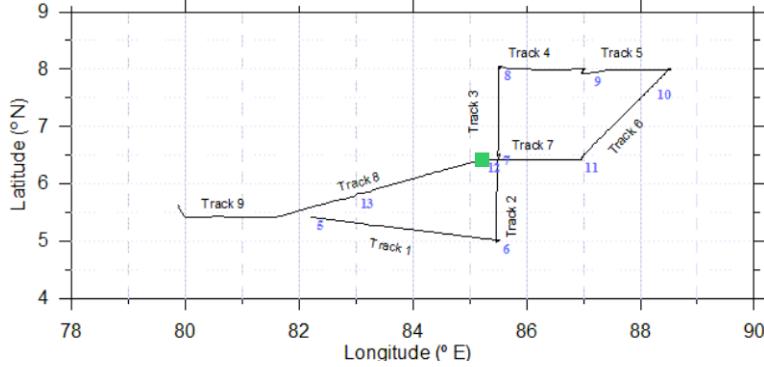
**B.** During August 3-16, 2015, UND PhD student Annunziata Pirro and a group of NARA scientists participated in the 1<sup>st</sup> leg of the R/V Revelle cruise in the southern BoB (Chief Scientist: Dr. H. Wijesekera). They helped to successfully recover six long-term NRL mooring deployed in the area during a December of 2013 cruise, and participated in a special 24-hour experiment focused on internal-wave dynamics and shear instability in the BoB pycnocline and small-scale dynamics of the surface layer (Fig. 1). Valuable ADCP data were collected along the ship tracks between the moorings to shed light on the spatial structure of the upper layer currents in the area associated with southwest monsoons.

**C.** CTD and ADCP measurements, conducted over 20hours at a station in the southern BoB onboard R/V Roger Revelle in July 2014, were processed and analyzed. Some salient results are outlined below.

## RESULTS

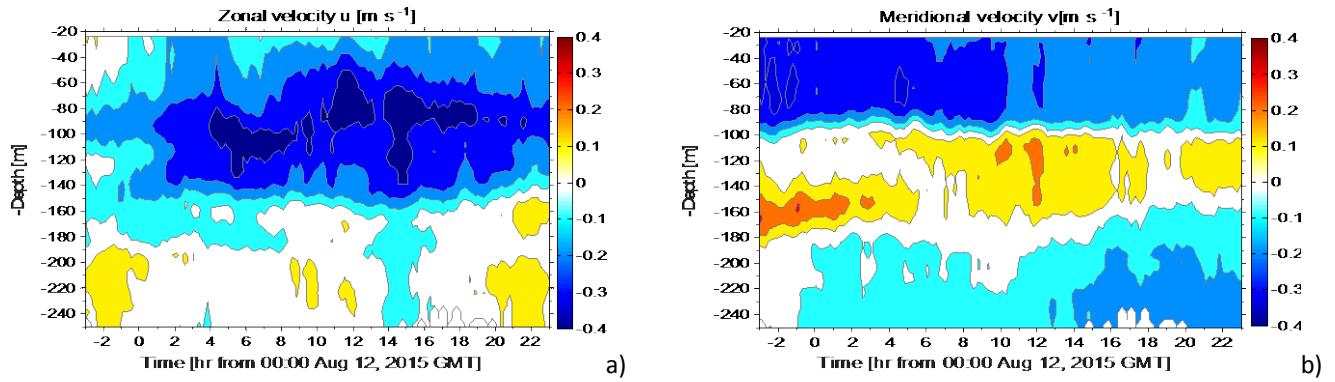
### A. Preliminary analysis of shipboard ADCP data in Southern BoB (R/V Roger Revelle, August 2015).

The shipboard ADCP data revealed the north-eastward flow in the upper layer ( $z < \sim 120m$ ) between 80°E – 84.6°E and 5.62°N - 6.25°N, which is a signature of the Southwest Monsoon Current (SMC). The observations suggest that SMC flows northeastward at least up to 8°N and 85.5°E with a predominantly northward velocity component of about 0.6 m/s. Data collected along the zonal transect 8°N, 85.5°E – 88.5°E show mostly eastward flow at the western half of the section. Thereafter, the flow gradually turns toward southwest. This suggests the presence of large mesoscale structures in the study area.



**Figure 1.** The shipboard ADCP measurements in the southern BoB during the summer cruise of R/V Roger Revelle (days of August 2015 are in blue). The 24 hr CTD station taken on Aug 12 is shown by the green square.

The remnant mixed layer (RML) depth was  $\sim 80$  m, in which the temperature and salinity varied between  $\sim 28.68 - 28.73^\circ\text{C}$  and  $\sim 34.706 - 34.723$  psu, respectively. The diurnal mixed layer deepens to  $\sim 20$  m, with the temperature increasing by  $0.1^\circ\text{C}$  but without change of salinity. A strong vertical shear was observed below the bottom of the mixed layer (Fig. 2).



**Figure 2.** Zonal (a) and meridional (b) components of the flow during 24 hr of CTD measurements at the station shown in Fig. 1 by green square.

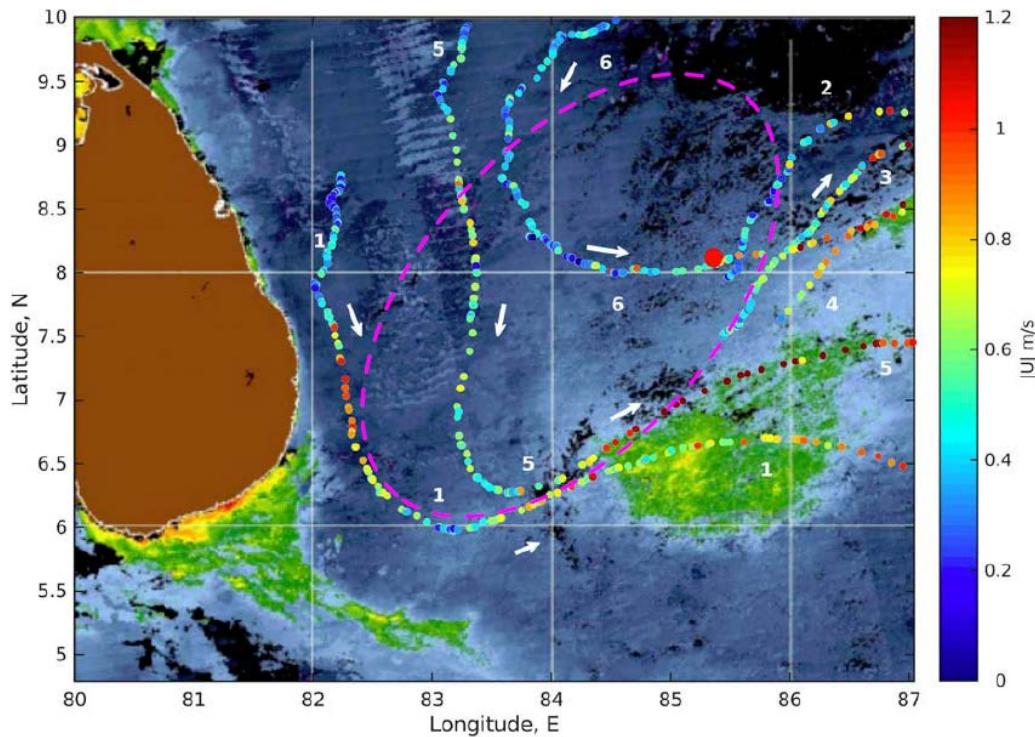
In RML, the current was predominantly directed southwest, but in the thermocline the westward component intensified and a northward component appeared. Between 200 and 250 m, the current turned again to the south, with negligible zonal component. The analysis is continuing, focusing on the characteristics of shear instability and internal waves in upper thermocline with respect to the multi-layered structure of the flow.

## B. Stratification and currents in the Southern Bay of Bengal (R/V Roger Revelle Cruise, 2014).

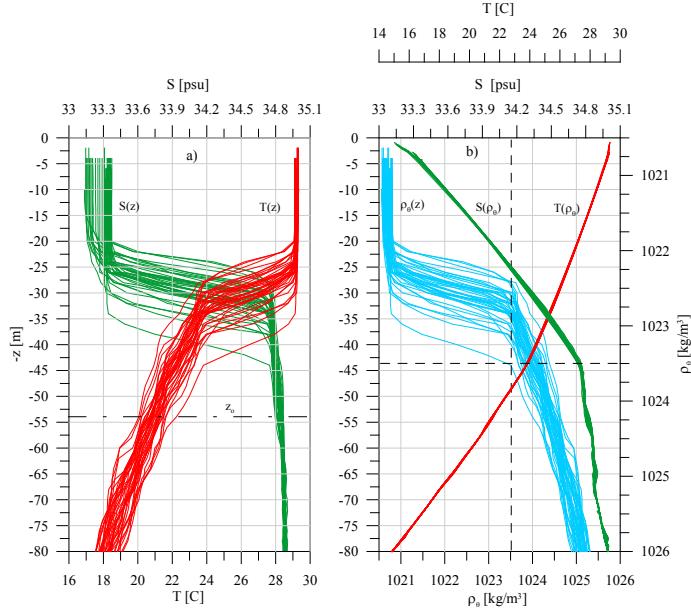
The CTD, ADCP, and acoustic backscatter profiles (down to 150 m) taken over 20 hours and the temporal CTD measurements at  $z = 54$  m taken in the pycnocline were at the northeastern periphery of the cold Sri Lanka Dome (SLD), as suggested by a composite of satellite images and drifter trajectories in Fig. 3. The observed transport of more saline, slightly cooler water in the surface layer can be

attributed to the circulation associated with the SLD that has been already developed in the region at the end of June in response to cyclonic curl of the local wind field stress. In the beginning of July, the SLD was found to stretch along a northeastern-southwestern axis, at the same time moving slightly to the west.

The thermohaline structure at all depths below the upper mixed layer (see all 41  $T(z)$ ,  $S(z)$  and  $\rho_\theta(z)$  profiles in Fig. 4a) is embedded with internal-wave perturbations, causing relatively wide scatter of the vertical ( $z$ ) thermohaline profiles (Fig. 4a).

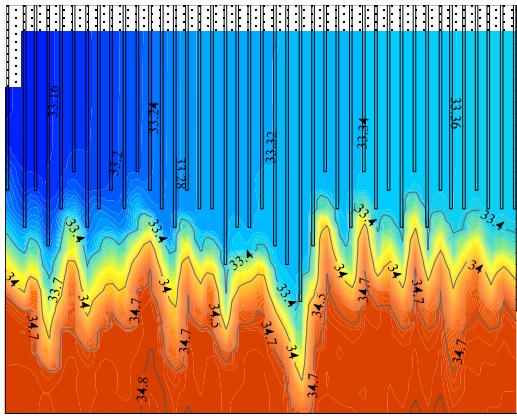


**Figure 3.** The weekly composite (June 30 – July 3) image of the BoB ocean color, showing enhanced chlorophyll concentration (green regions) associated with phytoplankton blooms (courtesy - Dr. H. Wijesekera). A large red circle at  $8^{\circ}7.2'N, 85^{\circ}21.5'E$  is the site of 20-hr profiling series. Directions (white arrows) and velocities (color pallet) of six drifters are shown along their trajectories. The averaged velocities are  $\sim 0.42$  and  $0.89$  m/s, respectively, for drifters No 2 and 4. The magenta dashed ellipse indicates possible region occupied by SLD in June – July of 2014.



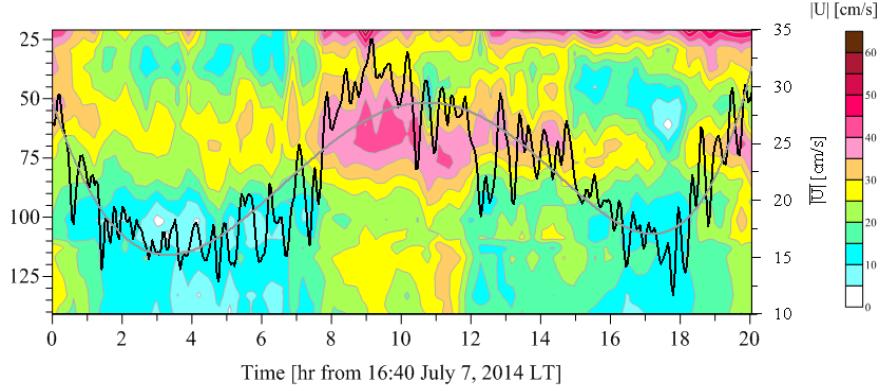
**Figure 4.** Temperature, salinity, and potential density profiles in the upper 80 m and profiles of  $T(z)$ ,  $S(z)$  and  $\rho_\theta(z)$  in the same depth range;  $z_0$  is the depth where CTD obtained time traces for ~30 mins between the casts. Dashed lines in the right panel indicate the lowest boundary ( $z_{plb}$ ) of a sharp thermohalocline at  $\rho_\theta = 1023.5 \text{ kg/m}^3$ .

The scatter essentially vanished when  $T$  and  $S$  are plotted as a function of the potential density [ $T(\rho_\theta)$  and  $S(\rho_\theta)$ ]; see Fig. 4b. Under moderate winds, the depth of the lower boundary of a sharp upper density interface  $z_{plb}$  appears to be almost unaffected by surface fluxes. Thus the variations of  $z_{plb}$  can provide an estimate of the amplitude  $\eta_{lf}$  of low-frequency linear internal waves, which heaves the entire pycnocline. It is shown in Fig. 4b that  $z_{plb}$  varies between 27 and 43 m, leading to  $\eta_{lf} \approx 16$  m. During the observational period, the surface mixed-layer depth (MLD) ranged between ~19 and 33 m. Fig. 5 shows that the MLD was influenced by air-sea interactions (the deepest MLD was observed in the early morning of July 8) as well as by higher-frequency internal waves in the underlying narrow pycnocline.



**Figure 5.** Salinity in the upper 42-m layer (colored contour plot) and the mixed layer depth (bars) at the test site.

Quasi-periodic oscillations of the MLD shown in Fig. 5 are well correlated with internal-wave induced displacements of the upper halocline, specifically during the daytime where sea surface fluxes do not change as much. The advection of higher salinity water near the sea surface by the northeastward currents causes the former to spread over the entire mixed layer (Fig. 5), indicating that the surface-layer currents may occupy the entire upper layer. Whether these currents penetrate downward to the pycnocline or not needs to be investigated using ADCP data.



**Figure 6.** The ccontour plot (color) of  $|U|(z, t)$  during 20 hrs. of CTD measurements. The depth-averaged (between  $z = 21$  and  $141\text{m}$ ) velocity magnitude is shown by black line; a polynomial approximation of these fluctuations is in grey.

The depth-time variations of velocity magnitude  $|U|(z, t)$  shown in Fig. 6 indicate the multi-layered structure of the mean currents. It appears that the strong northeastward surface current identified by drifter trajectories of Fig. 3 was confined to the upper mixed layer (above  $\sim z \approx 30 - 35\text{ m}$ ), which is especially true for the second half of the observational period. In a narrow upper pycnocline ( $z \approx 35 - 45\text{ m}$ ), the current magnitude is much weaker ( $|U| \sim 10\text{ cm/s}$ ) than that in the mixed layer. The flow

even exhibits a northwestward component after time  $t \sim 12$  hrs. (not shown), continuing to be influenced by anticyclonic circulation of the SLD. The upper part of the main pycnocline ( $z \sim 50 - 80$  m) is occupied by the strongest northeastward flow ( $|U| \sim 25-35$  cm/s), with the maximum speed observed around  $t \sim 9-10$  hrs). Below 80 m, the flow is relatively weak ( $|U| \sim 10-15$  cm/s), often showing the westward (a part of the anticyclonic) component.

The depth averaged ( $z = 21 - 141$  m) magnitude of horizontal velocity  $\overline{|U|}(t)$  shown in Fig. 6 suggests that the major enhancement of currents between  $t \sim 8$  and  $t \sim 12$  hr. is of tidal origin. This finding supports the notion that the largest vertical displacement of the sharp density interface between the surface mixed layer and the pycnocline [estimated as  $\eta_y \approx 16$  m; Fig. 4b] was induced by semidiurnal internal waves. The most striking feature of the  $\overline{|U|}(t)$  record, however, is well-identified higher-frequency oscillations of various periods, which could be of internal-wave origin. The analysis of such internal waves and shear instability are in progress.

## IMPACT/APPLICATION

This research project involves international collaboration between scientists from the US, Sri Lanka, and India. The program supports logistics of numerous US scientists operating in the Indian Ocean under ASIRI, EBOB and NASCAR projects. Capacity building is a key component, and to this end the UND group has trained Sri Lankan scientists of NARA to conduct microstructure, CTD and ADCP measurements as well as to process data. Mr. Priyantha Jinadasa, trained previously at UND, led a NARA group of scientists and students onboard R/V Roger Revelle during the 2015 research cruise in southern BoB.

## RELATED PROJECTS

The PIs are also working on an ONR 322-MMM funded project dealing with radio wave propagation in the marine boundary layer, where the role of UND is intense experimentation and theoretical developments on coastal marine boundary layer (N 00244-14-2-0004). In addition, Fernando is a PI of the ASIRI: Remote Sensing of Atmospheric Waves and Instabilities (RAWI) that deals with subseasonal atmospheric disturbances in the Indian Ocean (N00014-14-1-0279).

## PUBLICATIONS

Wijesekera, H.W., T.G. Jensen, E. Jarosz, W.J. Teague, E.J. Metzger, D.W. Wang, U. Jinadasa, K. Arulananthan, L. Centurioni, and H.J.S. Fernando. 2015. "Southern Bay of Bengal currents and salinity intrusions during a fall monsoon transition", *J. Geophys. Res. Oceans* [in press].

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Lozovatsky, I., S.U.P. Jinadasa, J.-H. Lee, and H.J.S Fernando, 2015. "Internal waves in a summer pycnocline of the East China Sea", *Ocean Dynamics*, **65**, 1051–1061, doi: 10.1007/s10236-015-0858-2.

Lozovatsky, I., S.U.P. Jinadasa, H.J.S. Fernando, J.-H. Lee, and C.-S. Hong, 2015. "The wall-layer dynamics in a weakly stratified tidal bottom boundary layer. *J Marine Res.*, [in press].

## HONORS/AWARDS

Enrico Marchi Award Lecture, Italian Hydraulics Association (June 2015, Fernando); Hong Kong University of Sciene and Technology (HKUST) Advanced Institute Distinguised Lecture of the HK Jockey Club (December, 2014, Fernando).